

Appendix B

DETAILED DESCRIPTIONS OF ECOSYSTEMS AND RESEARCH AND DEVELOPMENT NEEDS

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1. **Forests** (Rich Birdsey, Mac Post, Marilyn Buford, Ken Skog)

Long-term baseline estimates show that increases in biomass and organic matter on U.S. forest lands from 1952–1992 added 281 MMTC/year of carbon to forest ecosystems (25% of U.S. emissions for the period). Projections suggest continuing increases averaging 177 MMTC through 2040. For the period 1990–92 approximately 250 MMTC/year were sequestered in standing trees (~50%), and forest floor/coarse woody debris/ soils (~50%). The gain in forests is net of wood removed for products, and net of mortality from all causes including fire, pests, and disease. Carbon in wood used for products in 1990 was added to the pool of carbon in products in use, and products in landfills—for an additional net increase of carbon in products of about 60 MMTC/year.

Research on basic processes, measurement and monitoring, implementation methods and risk assessment in the forestry sector can provide cost-effective, environmentally sound methods in which to sequester more carbon. But, evaluation of the most effective forestry sector methods requires life cycle analyses that compare tradeoffs among alternate ways to use land area (forest and nonforest) for products for sequestration, and among alternate products (forest- and nonforest-based) to satisfy end use-needs. With that caveat, it is clear that research in a number of areas can improve forest sector contributions to sequestration. Areas where research is needed to improve cost effectiveness and environmental effects knowledge include: afforestation of marginal cropland; reducing deforestation; reforestation and improved forest management for sequestration; substituting wood products for more energy intensive products; reducing energy use in timber growing, harvesting, product production, and in end use; reducing wildfires; use of biomass fuel in place of fossil fuel with regrowth of biomass; increasing the amount of carbon in durable wood products and uses; increasing paper and wood recycling; planting trees in urban and suburban areas; enhancing soil carbon through species selection and management practices, including understory and ground cover management.

Current capabilities

Research is conducted in a broad range of forest sector disciplines that contribute to an understanding of, and means to alter, carbon accumulation in forests and forest products. These include soil science, tree physiology, tree genetics, ecological systems, forest pathology, forest entomology, forest mycology, fire science, forest mensuration, silviculture, forest management, forest economics, forest operations, wood products technology, and pulp and paper science.

Future needs

Research needs to be focused on (1) understanding basic biological, industrial, and socioeconomic processes that can increase sequestration in the forestry

sector, (2) measurement, monitoring, and modeling of ecosystem function and the forestry economic sector to evaluate the effectiveness of means to alter sequestration, (3) evaluation of alternative combinations of alterations to the forestry sector to increase sequestration and compare them to other uses of land and use of nonwood products for end-use needs (life cycle assessment), and (4) evaluation of risks of unwanted changes to ecosystem functions.

Strategies and objectives

Afforestation of marginal cropland and pasture. Substantial gains in carbon storage in biomass and soils on afforested lands are possible. This technology is limited primarily by the availability of suitable land (for ecological or economic reasons), nursery capacity, willingness of landowners to participate, and availability of technical assistance. Size of program and cost estimates vary widely because of differences in how and where proposed programs would be implemented and because of differences in carbon accounting. If the new forest land is managed for wood products, then the disposition of carbon in wood products, byproducts, and disposal must also be considered.

Improved forest management. There are opportunities to improve carbon storage by changing silvicultural practices on certain sites and forest conditions. The magnitude of increased carbon storage may be difficult to quantify since silvicultural practices are usually developed and applied for another purpose, such as increasing timber growth, and will not necessarily increase biomass growth and soil carbon storage. Nevertheless, some forest stands may not be growing at biologically potential rates because of suboptimal stocking levels. These stands offer the best opportunities for enhanced carbon storage. Also, silvicultural practices may be designed to maximize the amount of carbon eventually stored in harvested wood products.

Reduce conversion of forest land to nonforest use (reduce deforestation). Conversion of forest land to nonforest use usually means permanent loss of all or a substantial part of live biomass and reduction of organic matter in soils and the forest floor. CO₂ and other greenhouse gases are emitted when the removed biomass and organic matter is burned or decomposes. Some carbon may be sequestered in wood products if the removed biomass is utilized. Protecting and conserving forests should maintain or increase carbon pools in the short term, as long as natural disturbance rates do not reach catastrophic levels.

Increase sequestration of carbon in wood and paper products. Wood harvested from forests remains sequestered and is emitted to varying degrees depending on how products are made, used, and disposed of. Sequestration in products and uses can be increased by altered processing methods, shifts in products used, shifts in end-use durability, and shifts in landfill management. Sequestration in forests and products can be increased by coordinated understanding of forest ecosystems and products utilization.

Objectives

Above-ground

- Increase and maintain area of forest cover.
- Maximize biomass accumulation.

- Maximize average standing stock of biomass.
- Increase carbon retention in wood products and landfills.

Objectives**Below-ground**

- Increase and maintain area of forest cover.
- Increase soil organic matter on depleted soils.
- Minimize soil and litter disturbance during forest operations.
- Employ management techniques that increase soil organic matter in existing forest.

Research and development needs understanding**Above-ground**

- Develop genetically improved plantation species to maximize growth and wood density.
- Develop silvicultural practices (e.g., stocking control, understory management, and prescribed burning) that maximize biomass accumulation.
- Enhance wood and paper products characteristics that increase sequestration (e.g., durability, lignin, recyclability).
- Improve understanding of the interactions between natural disturbances (weather, fire, pests), management practices, and forest protection, with regard to impacts on long-term carbon storage.
- Determine socioeconomic causes (e.g., social institutions) of deforestation.

Below-ground

- Develop silvicultural practices and/or selections of species or genotypes that result in a higher humification efficiency (i.e., increase the fraction of dead organic matter that is converted into stable soil humus during decomposition). Much of the litter applied to the surface, including most wood, never enters the soil as humus. Material that enters via the soil has a higher humification efficiency. Material that has a higher lignin content has a higher humification efficiency. Research is needed to assess species or management that affects allocation and tissue composition on soil carbon accumulation.
- Litter and soil decomposition is affected by a number of physical, chemical, and biological factors. Physical factors amenable to management include soil temperature and moisture. Chemical factors include nutrient content and pH. Biological factors include microorganisms, micro- and macro-invertebrates. Research to determine manipulations of these factors to decrease decomposition rates without drastically affecting tree growth is required. Research to create deeper rooting zones would also be important.

Measurement**Above-ground**

- For major ecoregions, quantify the potential biomass gains from converting agricultural use to forest using different stand establishment techniques and species (comparative cross-sectional studies; existing long-term research sites).
- Identify existing forest conditions that result in suboptimal biomass accumulation.

- Compare carbon mitigation of burning wood, recycling wood/paper, shifting to longer-lived uses, landfilling (with limited decay).
- For monitoring and verification of changes in above-ground carbon storage, improve and integrate use of data from forest inventory, remote sensing, and Ameriflux collection methods.

Below-ground

- For major ecoregions, quantify the potential soil carbon (including organic layers) gains from converting agricultural use to forest using different stand establishment techniques and species (comparative cross-sectional studies; existing long-term research sites).
- For monitoring and verification of changes in below-ground carbon storage, improve national forest inventory collection of periodic data on soil organic matter, litter, and coarse woody debris.

Implementation

Above-ground

- Develop and use national models to identify high sequestration combinations of genetically improved species, forest management intensities, products utilization, and landfill management.
- Perform life cycle analyses for major tree species, silvicultural systems, and wood products. Note that this involves analysis of energy inputs throughout the life cycle.

Below-ground

- Develop methods to improve the efficiency of the humification process for logging residue.

Assessment

- Evaluate the impact of changes in forest growth/sequestration on essential ecosystem functions.
- Evaluate the risk that disturbances to forests (e.g., fire, pests) and climate change induced changes in productivity or species viability may thwart various activities to increase sequestration.

General

- Develop interagency coordination of research and interagency coordination of strategies to increase sequestration.

Links to other ecosystems

- Use comparative studies to evaluate carbon tradeoffs from converting agricultural use to forest use.
- Understand the socioeconomic tradeoffs of converting agricultural use to forest use.
- Determine the impacts of deforestation to agricultural or developed use on major forest ecosystem carbon pools.

2. Agricultural and Grassland Ecosystems (Keith Paustian, Julie Jastrow, Margaret Torn, Ron Follett, Mary Firestone)

The carbon sequestration potential in agricultural and grassland ecosystems is primarily centered in the soil. Standing stocks of above-ground biomass are modest (typically < 10 Mg C/ha) compared to forests and, in the case of annual crop systems, may be entirely absent for part of the year. In contrast, grassland and agricultural soils may contain several hundred mg/ha of carbon, comparable to amounts above-ground in densely forested communities.

The high levels of carbon achievable in grassland and agricultural soils are the result of the accumulation of plant and microbial-derived residues which become increasingly recalcitrant through recurring cycles of decomposition by soil organisms. In addition, association of organic matter with soil minerals, through binding to colloidal surfaces and occlusion within soil aggregate structures, reduces their accessibility to microbial decay, enhancing organic matter accumulation.

Soil carbon levels are determined by the balance of carbon additions from roots and above-ground litter and the decomposition rates of the organic matter present in soils. Hence, carbon sequestration (i.e., increasing standing stocks of carbon) can be promoted by increasing carbon input rates, decreasing decomposition rates, or both. Carbon input rates are a function of the net productivity of plants, the allocation of that productivity between removals (i.e., harvest, fire) and residues returned to soil, and organic matter imports (e.g., manure, sludge). Soil organic matter decomposition rates depend on the composition and activity of soil organisms, which are influenced by their abiotic environment (temperature, moisture, aeration, mineral nutrients, pH), the physiochemical quality of the organic substrates (its chemical composition, particle size) and the accessibility of these substrates to soil organisms (influenced by soil texture and soil structure relationships). Ecosystem management to increase carbon stocks will be based on the manipulation of these controls on inputs and decomposition rates.

Current carbon sequestration capabilities of grassland and agricultural ecosystems

Cropland currently occupies about 150 Mha of land area in the U.S. (contiguous 48 states) with an additional 14 Mha of formerly cultivated lands in grassland and forest set-asides (mainly Conservation Reserve Program Lands). Agricultural and set-aside lands represent about 20% of total land area of the U.S. Soil carbon stocks (0–1 m) under cropland are on the order of 15–20 Pg (based on extrapolations from surface soil estimates (0–30 cm) by Kern and Johnson 1993), compared to the 60–80 Pg total for all ecosystems in the contiguous U.S. (Kern 1994, Waltman and Bliss 1997). Historically, these lands have suffered a net loss of carbon, on the order of 5–6 Pg, following conversion of the native ecosystems to cropland. More recently, increased productivity and improved management practices have probably reversed this trend such that overall carbon levels have now stabilized or begun to increase (Cole et al. 1993, Lal et al. 1998). Existing management practices which are responsible for improving carbon levels include reduced tillage intensity, productivity increases through genetic improvements

and increased management inputs (fertilizer, pesticides, irrigation); intensified crop rotations (e.g., reduced summer-fallow); and set asides of marginal cropland to perennial vegetation, mainly grasses (Paustian et al. 1997). Recent estimates of the potential for carbon sequestration in U.S. agricultural soils, using existing technologies, are on the order of 50–200 Tg/year over the next 2–3 decades (Bruce et al. 1998, Lal et al. 1998). The range of these estimates reflects both uncertainties in carbon accumulation rates for different practices and soil/climate conditions and uncertainty in the projected rates and extent of adoption of carbon conservation practices.

Grasslands include both extensively managed native rangelands as well as intensively managed pastures. In the lower 48 states, there are about 160 Mha of nonfederal rangelands and 50 Mha of pastures (1992 National Resource Inventory). Conventional management factors that can impact soil carbon levels on grasslands include grazing management, burning, species selection, and production inputs (i.e., fertilizer, irrigation). Intensively-managed grasslands (i.e., pastures), where productivity and management inputs are relatively high, probably have the greatest opportunities for increasing soil carbon through improved practices such as rotational grazing and application of fertilizers (Nyborg et al. 1997). On rangelands, traditional management is largely restricted to manipulating grazing intensity, which has variable impacts on soil carbon. In general, where vegetation cover and production of rangelands are not adversely affected by grazing, there is little change in SOM (Burke et al. 1997, Milchunas and Lauenroth 1993). Compared to agricultural lands, there is less field data upon which to base estimates of current carbon sequestration potential in grasslands. Bruce et al. (1998) estimated potential rates of sequestration for U.S. pastureland at 10 Tg/year. The greatest opportunities for carbon sequestration in rangelands involves rehabilitation of degraded areas. Unfortunately there is no existing national data base from which to estimate rangeland conditions and the potential for improvement of degraded rangelands. Widespread but slow rates of carbon sequestration may be occurring in many grasslands due to CO₂ fertilization and increased anthropogenic nitrogen deposition, but reliable estimates are currently lacking.

Strategies and objectives for carbon sequestration in grassland and agricultural ecosystems

Strategies for increasing carbon stocks in these soils revolve around maximizing the amount of carbon that can be delivered to the soil and subsequently maximizing its residence time in the soil (by reducing rates of decomposition). Ultimately nearly all carbon that enters the soil is recycled back to the atmosphere, but the amount of carbon in the soil will increase in direct proportion to its mean residence time. Since croplands and grasslands represent the primary food production systems for society, it's important that carbon sequestration strategies be compatible with the maintenance of food and feedstock supplies. Fortunately, many measures to increase primary productivity also increase plant residue production, and increasing soil carbon levels are generally beneficial for maintaining highly productive systems. However, tradeoffs do exist. For example, increasing the yield component of crop plants without increasing total net productivity will come at the cost of reducing carbon inputs to soil, and

retirement of cropland to perennial grassland (or trees) may yield higher carbon sequestration rates but with a loss of food production capacity.

A variety of strategies can be conceived to increase net primary productivity and carbon inputs to soil, through increased photosynthetic efficiency, increased nutrient and water use efficiency, and shifts in allocation of photosynthate to the below-ground component. For extensively managed grasslands (rangelands), strategies to increase carbon inputs would be based largely on restoring degraded, poorly managed areas through control of invasive species, elimination of severe overgrazing, and active restoration on severely degraded rangelands. In pastures and croplands, a wider variety of more management-intensive strategies exist, including improved grazing management (e.g., rotational grazing); fertility management; pest control; species selection; and genetic improvements, including plant bioengineering.

On the decomposition side, strategies include manipulating the abiotic environment in favor of plant growth vs microbial (decomposer) activity, while still maintaining the function of the soil microbial community. For example, increasing water use efficiency of plant production (e.g., reduced summer-fallow, higher plant density, more efficient plant water extraction), reduces “excess” water, producing drier soils and reduced microbial activity. Many grass and crop species have lower temperature optima than the majority of microflora. Thus somewhat cooler temperatures (e.g., with use of surface mulches) may reduce decomposition rates while optimizing plant carbon inputs. Soil organic matter typically shows a substantial increase in age with depth (e.g., Paul et al. 1997) due, in part, to lower rates of decay at depth, from lower temperatures, reduced aeration and other factors. Thus, developing and/or using deeper rooting plants can place more carbon in locations where its residence time is increased. The susceptibility of plant residues to decay is influenced by their chemical composition, so that increasing the amounts of recalcitrant substances (e.g., lignin, polyphenols) in residues could enhance carbon storage. Decomposition rates in soils are inhibited by the close association of organic substances with mineral colloids (clays, oxides) and the occlusion of organic matter within soil aggregates. Tillage tends to reduce aggregate stability; thus reducing or eliminating tillage can help maintain the physical protection capacity of soils. Development of reduced and/or zero-tillage systems for a wider variety of crops and environments is an important strategy. Increased use of perennial grasses and legumes, alone or in rotation with annual crops, is effective in building soil carbon stocks. Other opportunities might include the use of artificial colloidal amendments to sorb and “protect” organic matter in soils. Finally, direct manipulation of microbial communities through bioengineering could conceivably be used to reduce decomposition rates, although the unlikelihood of success (i.e., a reduced ability to metabolize organic matter would make for poorly competitive organisms) and the potential for undesirable side effects (i.e., disruption of the biogeochemical cycling function of soils) argue against the desirability of such strategies.

Strategies to sequester carbon in agricultural and grassland ecosystems also need to factor in the carbon cost in terms of fossil fuel subsidies (e.g., fertilizer and herbicide production, farm machine use, irrigation pumping) for various

production practices, as well as the potential effects on other soil-emitted greenhouse gases, chiefly N_2O and CH_4 . Previously described strategies directed at increasing primary production efficiency (i.e., increased nutrient and water use efficiency), increased use of nitrogen fixation by legumes in crop rotations (to replace fertilizer nitrogen), increase dependence on mycorrhizae and adoption of zero-tillage systems (Frye 1984) would reduce fossil carbon requirements. Agricultural ecosystems are usually net sources of N_2O , particularly from soils with high amounts of inorganic nitrogen. In addition, methane is generated by ruminant livestock and also by waterlogged soils, notably rice paddies. While CO_2 is much more abundant in the atmosphere, N_2O and CH_4 are, molecule for molecule, more potent greenhouse gases relative to CO_2 . The impact of carbon-sequestering practices on the potential emissions of these other gases, therefore, cannot be ignored. Although the secondary effects of carbon-conserving practices are often difficult to quantify, any proposed practice should be carefully assessed to ensure that the benefits in carbon stored are not seriously reduced by the emission of other gases.

Research and development needs

Research is needed to promote a better understanding of key soil processes, in order to assess how and to what degree they can be manipulated to promote carbon sequestration. In addition, there are major R&D needs that relate to the estimation and quantification of current and future carbon stocks as a function of environmental and management factors. These later needs cut across all the major ecosystem types.

For specific R&D priorities related to understanding controls on primary productivity and plant allocation, we refer to the section under Biomass Croplands. R&D priorities related to soil processes and controls and inventories of current and future carbon stocks are outlined below:

Research needs for fundamental understanding of soil processes and controls

- A. Increase depth of soil carbon
 - 1) Species-soil-climate interactions controlling root depth distribution
 - 2) Controls on decomposition at depth
 - 3) Deep movement of organic and inorganic carbon
 - 4) Effect of tillage systems on rooting depth
- B. Increase root mass
 - 1) Controls on above-ground to below-ground carbon allocation for different plants
 - 2) Species selections that dramatically increase root mass
 - 3) Nutrient controls and feedback on productivity
 - 4) Adaptations to CO_2 increases, temperature increases, and pH tolerance
- C. Transform Labile carbon to Recalcitrant carbon
 - 1) Isolation and characterization of recalcitrant organic matter
 - 2) Controls on formation of recalcitrant SOM
 - 3) Role of soil structure in SOM physical protection
 - 4) Role of soil minerals and cations on chemical protection of SOM
 - 5) Effect of litter quality on decomposition rate

- 6) Effect of rhizodeposition and exudation on decomposition rate
- 7) Effects of microbial community structure on SOM cycling and stabilization
- D. Create less favorable abiotic environment
 - 1) Soil moisture-microbial community interactions affecting decomposition
 - 2) Community and biome variability in thermal responses of microorganisms
 - 3) Effect of nitrogen addition (as fertilizer, deposition, biological nitrogen-fixation) on decomposition

Research needs for improving inventories of carbon stocks in agricultural and grassland ecosystems

- A. Dynamic inventories of land cover and land management system distributions
 - 1) Development of coverages with improved spatial resolution to differentiate fragmented land covers
 - 2) Improved differentiation of crop and grassland species assemblages
 - 3) Remote sensing techniques to resolve different management regimes within landcover/vegetation types (e.g., tillage management, cover crops, grazing intensity)
- B. Survey data
 - 1) Global metadata compilation of national land use/management information
 - 2) Standardization and/or cross comparison of survey/inventory approaches and definitions
 - 3) Synthesis (within United States) and cross validation of national level survey data (e.g., USDA/NRI, FS, BLM, USDA/ERS)
- C. Information on distribution and characteristics of soils
 - 1) More information on soil carbon concentrations at depth
 - 2) Synthesis and integration of data from distributed pedon data holders (e.g., universities, state agencies)
 - 3) Standardization (international) of attributes (e.g., carbon analytical methods, bulk density, texture, drainage, and depth) and techniques needed to estimate soil and litter carbon stocks and soil bulk density (e.g., as part of USDA/NRCS and ISRIC collaboration).
 - 4) In situ, nondestructive determinations of soil carbon

Needs for quantification and prediction of carbon sequestration

- A. Development of modeling approaches
 - 1) Testing and refinement of models for less studied systems; for example, flooded and poorly drained soils, highly weathered soils (e.g., Ultisols, Oxisols), volcanic-derived soils
 - 2) Representation (in simulation models) of SOM fractions that are analytically determined, concomitant with experimental science to improve functionally meaningful characterization of SOM
- B. Enhancement of SOM monitoring networks
 - 1) In field relocateable, resampling points designed to minimize spatial variability, tied into existing monitoring systems (e.g., NRI). Measure change under a variety of cropping/grassland systems (steady-state/aggrading/degrading) in a variety of climates and soil types

- 2) Increased deployment of ecosystem CO₂ flux systems, coordinated so as to leverage information from existing long-term experimental sites (e.g., establish new flux measurements for soil, crop and management variables where long-term experimental records exist) and intensified soils research at existing CO₂ flux tower facilities
- C. Coordinate and synthesize spatially referenced data coverage for important model driving variables.

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3. Biomass Crop Lands (Lynn Wright, Sandy McLaughlin, Jerry Tuskan, Don Reimensneider, and Carl Trettin)

Biomass production and harvesting systems are being developed to optimize above-ground plant productivity per unit area in a way that conserves and improves soil resources, maintains or improves water quality and wildlife habitat, provides profit potential to the landowner, and supplies low-cost, uniform feedstocks to energy providers as a means of displacing fossil fuel. The crops under development for this land use are primarily perennial crops, including several grass and tree species worldwide. These crops are grown using agronomic techniques such as cultivation or herbicide use for site preparation, fertilization, pest and disease control for crop maintenance, and periodic removal of the above-ground portion of the crop. The grass species are harvested annually or more frequently while the tree crops have 3–10 year harvest intervals. It is generally assumed that the trees or grasses will be grown in relatively large blocks for ease of harvest, handling, and utilization. Alternative methods of biomass production include mixing annual and perennial crops (agroforestry), using shelterbelts or riparian zones to produce biomass, and mixing species in production stands.

A critical assumption for carbon sequestration analysis is that these perennial crops will be established on idled or surplus crop or pasture land, on cropland that is occasionally flooded, or on lands marginally profitable for annual crop production because of poor soil quality, erosion sensitivity, nutrient degradation, or other reasons. The rate of conversion of agricultural cropland to biomass cropland will be economically and policy driven but is also dependent on the development of new, more efficient biomass production and bioenergy conversion technologies. In some areas of Europe, idled agricultural cropland is already being converted to biomass crop production for energy end-use. In other places, such as the United States, the biomass cropping systems described above are being used to produce fiber products with energy production as a by-product.

Current carbon sequestration capabilities of biomass cropland

The greatest carbon emission reduction gain from biomass cropland will be obtained when economic or policy conditions result in the use of biomass cropland to produce feedstocks that substitute for carbon emitting fossil fuels such as coal and oil. Since adequate economic and policy drivers are not yet in place in most areas of the world, very little land currently is managed as biomass cropland. In the United States about 50,000 ha have been converted from agricultural cropland to production of woody crops. Several million ha of cropland were converted to switchgrass and other grass mixtures as part of the Conservation Reserve Program in the United States from the mid-1980s to mid-1990s. However, those lands have not received fertilization or pest control and thus are not highly productive. Similar types of land conservation programs were instituted in Europe for similar reasons. In addition, many parts of the former Soviet Union have large amounts of idled cropland reverting to natural ecosystems with the change from centrally managed to private managed agricultural systems. For purposes of a carbon sequestration analysis, some combination of the current carbon sequestration capabilities of annual crop systems and pastureland should be used as the biomass cropland baseline.

Strategies and objectives for biomass cropland carbon sequestration

Since biomass cropland systems are at a very early stage of development, the opportunity exists to select and develop perennial plant species and management systems that optimize both above-ground production and below-ground carbon sequestration while providing profit to the landowner. The primary research strategy here is to increase the per unit land area rate of carbon fixation in the above-ground (economic) portion of the perennial plant biomass by 2 to 4 times. A policy/economic strategy is to develop markets for biomass crops to assure periodic removal of the crops for sequestration in bioproducts (e.g., wood products, bioplastics, etc.) and bioenergy (fossil carbon substitution). Development of the markets could be enhanced by genetically improving the characteristics of perennial biomass crops for bioenergy or bioproduct utilization

One risk associated with biomass croplands is public acceptance of land use change. Because of this, biomass croplands will have to provide more than just carbon sequestration and energy benefits in order to be accepted. Some level of optimization of carbon sequestration and plant productivity may have to be sacrificed in order to assure that water quality, soil conservation, and wildlife benefits are provided as an inherent component of biomass cropland ecosystems. Thus realizing the high rates of carbon sequestration that deployment of biomass production systems can offer additionally requires; (1) land use policy that facilitates biomass cropland implementation without violating strongly held ideas about land use, (2) multiple environmental benefits associated with the land use change and, (3) achievement of high carbon fixation and storage rates with low fossil carbon inputs.

The amount of carbon sequestration in biomass cropland will ultimately depend on the scale of land use conversion that occurs. Conversion of between 10 and 15% of current crop and pasture land worldwide to biomass production appears to be a feasible goal that would not substantially impact food and fiber production and which could provide observable regional environmental benefits.

Research and development needs

All plant productivity research could benefit from improving our understanding of plant and soil processes. Research on plant process understanding must integrate with genetic improvement and crop management activities focusing on carbon sequestration impact. Genetically improved stock should optimally combine high-yield potential, with disease and pest resistance, high water-use and nutrient efficiency and optimal feedstock properties for conversion. Genetic potential needs to be achieved in concert with crop management techniques that minimize carbon inputs but assure sustainability of yields over time. Functional genomics will use molecular genetics to identify and modify plant growth and development processes, including individual gene expression, host-microbial interactions, all physiological responses, and plant assembly mechanisms. Integrated physiology, entomology, pathology, and agronomic studies are needed to elucidate plant growth and stress resistance mechanisms (i.e., studies focused on CO₂ fixation and respiration processes, carbon allocation, efficiency of carbon capture per unit of nutrients and water available, and pest and disease resistance are required). The selection and deployment of improved planting stock and crop management techniques must be optimized for each soil type and climatic zone.

Similar to most plant ecosystems, process understanding is critical to improving below-ground carbon sequestration in biomass croplands starting with improving our understanding of the processes controlling the movement of above-ground carbon to soil carbon pools. Carbon storage process studies should include; (1) determination of how carbon fractionation influences labile and recalcitrant forms of carbon, (2) quantification of how existing carbon levels affect storage rates and, (3) determination of factors affecting the rate and form of downward carbon migration in soils. The process research should be supplemented with extensive surveys documenting how carbon forms vary with soil type, depth, temperature, physical properties, and chemistry as well as types of crops and cropping strategy. In evaluating crops and cropping approaches it will be important to link effects of nitrogen management and tillage practices to carbon storage rates, stability of carbon gains over time, and the equilibrium conditions. Finally, a better understanding how climate change events (such as nitrogen deposition, regional ozone levels, changing precipitation patterns, and overall global warming) may feedback to affect carbon inputs and storage will add valuable information for predicting long-term effects.

The measurement and quantification research that would non-destructively determine carbon sequestration in the soil in biomass croplands would be very beneficial. Remote sensing approaches could also improve our ability to survey large areas of land thus predicting levels of standing biomass. Research to improve our understanding of the linkage between above- and below-ground carbon gains would be helpful in estimating soil carbon gains based on tons of biomass harvested annually.

Implementing the strategy for increasing carbon sequestration in biomass cropland requires the initiation of research that will lead to (1) technologies that are economically viable and environmentally sound and (2) analytical techniques that will assist policy makers in determining optimal land use allocation strategies for achieving carbon sequestration goals. Carbon sequestration will not increase in any ecosystem unless there are appropriate economic and policy drivers.

One risk associated with biomass croplands is public acceptance of land use change. This is part of the reason why biomass croplands will have to provide more than just carbon sequestration and energy benefits in order to be accepted by the public. Thus some level of optimization of carbon sequestration and plant productivity may have to be sacrificed in order to assure that water quality, soil conservation, and wildlife benefits are provided as an inherent component of biomass cropland ecosystems.

Linkages

Biomass cropland R&D will be similar to that proposed for traditional agricultural crops, intensively managed forests, and managed grasslands since in all cases, a major goal is the production of biomass for removal from the site. Improvement of plant growth on degraded ecosystems could also share some similarities in approach with biomass croplands, since stress tolerance will be a component of both systems.

Biomass and agricultural cropland R&D will differ in that the former will focus primarily on perennial plants and the latter on annual plants and that most of the products from biomass crops will have a longer sequestration residence time. Basic plant research may be able to address some topics common to both, but perennial and annual plants have very different requirements for survival, and thus many differences in basic plant mechanisms.

Biomass cropland and managed forest or grassland ecosystems will differ by the fact that biomass crops will likely be established on former agricultural lands that are carbon depleted, while forest and grassland soils will likely have less opportunity for soil carbon increases.

A major cross cutting issue is to develop appropriate decision models and analytical techniques for optimizing land use allocation under various economic and policy scenarios. In the context of this report, consistent decisions have to be made on accounting for carbon removed from sites, considering portions that return to the atmosphere with no fossil substitution and portions that are sequestered or substitute for fossil carbon.

4. Wetlands (Carl Trettin, Ron Thom, Patrick Megonigal, Walter Oechel)

Global wetlands cover about 7% of the total land surface, and contribute about 10% of the total global net primary productivity (NPP). Many systems have a high turnover rate (production:biomass) indicating loss and export rates are high. In addition, loss to sedimentation in deep portions of lakes and oceans may be great. Wetlands produce 40% of the global methane emissions. The degree to which wetlands produce methane is intimately tied to the hydrology of the system. Systems, such as rice paddies, that are wet much of the time, have greater methane emission rates. Marshes and some other wetland systems can be nutrient limited. Wetlands have the highest carbon density among all terrestrial ecosystems. Because of their low drought stress, high nutrient availability, and ability to expand below-ground biomass in enriched conditions, wetlands have a relatively great capacity to sequester additional carbon dioxide.

Wetlands sequester carbon through accretion of sediments and organic matter. Accretion is great in coastal systems where sediment input to estuaries is high. Marshes, in particular, form land through progradation. Very limited studies have shown that coastal marshes under enriched CO₂ conditions, can sequester more carbon in the below-ground biomass. Carbon sequestration through peat formation is an active process especially in boreal systems. Because of their position at the interface between land and water bodies, wetland export large quantities of carbon to deeper portions of lakes, estuaries and oceans, where carbon can be sequestered through burial.

Wetland soils contain a significant proportion of the terrestrial soil carbon (20–25%), despite the relatively small proportion of the total land area occupied. In North America, approximately 50% of the wetlands are forested. They are an important carbon sink, and a major source of atmospheric methane. Carbon dynamics in wetland soils also affect non-point pollutants, ground and stream water chemistry, and biogeochemical processes. Although soil carbon in wetlands is recognized as being an important component of global carbon budgets and future climate change scenarios, relatively little work has been done to consider the role of terrestrial ecosystems in managing carbon sequestration. Wetlands are among the most productive ecosystems in the world. They also have properties that reduce the rate of organic matter turnover from the ecosystem. Hence wetlands inherently have the two primary factors controlling carbon sequestration, (1) high rates of organic matter input, and (2) reduced rates of decomposition. There is considerable opportunity for managing that capability to affect enhance carbon sequestration while sustaining the other valued ecosystem functions. However, considerable research is needed to provide the knowledge foundation for the resource management decisions.

In the United States, 50% of wetlands have been lost or converted to other uses (e.g., crop and grazing lands). Globally the loss is undocumented, but could easily be as great. Sea level rise is causing net loss of some coastal wetlands, and carbon sinks in temperate and boreal wetlands have decreased by 50% (from 0.2 to 0.1 GtC year⁻¹) due to development and resource extraction. Loss in tropical systems could likely exceed this amount. The leading causes of wetland loss are conversion, deforestation, development, and hydrological modifications.

Because of the global losses of wetlands, restoration of damaged, degraded and converted ecosystems represents a major opportunity to improve sequestration in wetlands. We estimate that restoring 25% of the wetlands would result in an increase in carbon sequestration. Hydrological controls could be effectively used to produce a positive balance in favor of carbon sequestration vs methane emission. Some wetland systems are nutrient (nitrogen) limited to some degree. Hence, fertilization or other methods to introduce nitrogen into these systems could increase primary productivity and enhance carbon storage. Reduction in the rate of sea level rise would reduce the rate of conversion of intertidal wetlands to subtidal mud bottom. Massive restoration efforts presently underway on the Mississippi River delta through the Coastal Wetland Protection, Preservation and Restoration Act (CWWPRA) represent an excellent opportunity to evaluate the effects of large scale restoration on carbon sequestration and comparison of forest, shrub, and herbaceous wetlands.

Strategies

- Identify degraded wetlands and develop management/conservation strategies to rehabilitate processes that sequester soil carbon. These lands have the inherent characteristics to sequester large amounts of carbon; reestablishing anaerobic processes and managing inputs have the potential for large amounts of long-term carbon storage. Especially important opportunities exist in prior-converted agricultural lands.
- Implement vegetation management strategies that sustain the soil carbon resources while producing woody crops.
- Increase soil carbon storage by identifying sites that have high productivity potential through managing water and nutrient resources.
- Conserve wetland landscapes that are inherently effective at carbon storage.
- Mitigate carbon loss through created wetland systems.

Objectives

- Increase soil carbon sequestration in managed wetlands to rates above the norm for natural or unmanaged systems.
- Increase acreage of wetlands within selected landscapes thereby enhancing both above and below-ground carbon storage.
- Increase the volume of wood products derived from the resource that enter stable products classes.
- Implement planning / decision systems that consider carbon sequestration at the landscape level.
- Consider the value of carbon sequestration in designing mitigation projects.

There may be inherent limits on the potential for any given wetland to simultaneously have both very high productivity and extremely slow decomposition rates. Such limits will be important to understand if we wish to manipulate wetlands to enhance carbon sequestration. One limit that is incompletely understood in wetlands is the link between carbon and nitrogen cycling. Plants require a substantial nitrogen supply to support high photosynthesis rates. Most of the annual nitrogen demand in wetlands is supplied by decomposition of soil organic matter, a process that produces both plant available nitrogen and CO₂. Thus, wetlands cannot necessarily support high rates

of photosynthesis and low rates of decomposition simultaneously. A basic research needed in wetlands is understanding how nutrient inputs and hydrology can be managed to optimize net ecosystem production in wetlands.

Coastal marshes have high rates of primary production due to tidal subsidies of water and nutrients, and high rates of carbon sequestration in soils due to low decomposition rates and burial by sediments. Global sequestration in these systems is perhaps 0.025 to 0.05 Pg carbon per year. One of the largest coastal marsh systems is the Mississippi River delta, which has an area of ~30,000 km², roughly 10% of all coastal marshes. Both natural and artificial impacts are causing annual losses of 66 km² of freshwater and saltwater wetlands in the basin, and efforts to slow these losses are underway. Halting the current losses would save about 0.03 Tg y⁻¹ in soil carbon sequestration. Restoring these wetlands would increase this amount by perhaps 20-fold.

R&D Needs

Above-ground

- Improve the understanding of the processes controlling vegetative production and community dynamics.
- Improve the understanding of the hydrologic controls on above and below-ground carbon allocation and carbon uptake vs emission.
- Develop a modeling framework to consider the role of wetlands in carbon sequestration at the landscape scale.
- Develop an understanding of how wetland plants (i.e., trees) will respond to increased levels of atmospheric CO₂.
- Develop techniques to sustainably manage wetland ecosystems.
- Determine the differences among forest and herbaceous communities in carbon sequestration.

R&D Needs

Below-ground

- Improve the understanding of the processes controlling biomass allocation to roots among different wetland species.
- Develop an understanding of the role of mycorrhizae in carbon fixation and plant productivity.
- Determine how different land management practices affect soil carbon storage.
- Determine the feedback of changes in soil carbon storage on ecosystems functions (e.g., habitat, water quality, hydrology).
- Determine the interactions of nutrient levels, temperature, redox and organic matter quality on carbon turnover and sequestration.
- Determine the organic matter sources affecting soil carbon storage.
- Role of fire in limiting carbon sequestration.
- Explore opportunities for creating wetland/carbon storage systems as an integral components of the landscape. Such a system would provide environmental benefits (e.g., water quality, habitat, recreation) and provide long-term carbon storage.
- Improve the understanding of the hydrologic controls on processes controlling carbon sequestration.

Linkages

Wetlands are inherent to most landscapes where soil carbon storage is important. Accordingly, whether the management system is on the upland, adjoining the wetland, or directly within the wetland, wetlands are probably involved in attempts to affect carbon sequestration on the land. The linkages are controlled primarily by the movement of water. Hence understanding the functional linkages among ecosystems or management zones is critical to developing sustainable management systems. Wetlands effect soil carbon storage primarily as a result of reduced rates of organic matter turnover caused by anoxia. Factors affecting hydrology or aeration may affect the processes controlling soil carbon storage. Accordingly, there are direct linkages to land use (i.e., water use, waste disposal, urbanization) that must be considered at the landscape scale. Altered climates factors including temperature, precipitation, and atmospheric CO₂ should be expected to change wetland processes and carbon storage. Studies of the effects of climate change factors on wetlands have largely been ignored. Accordingly, there is a critical need to develop an understanding of climate change influences on wetland processes so that those influences can be considered in conjunction with current and planned management approaches.

There is considerable interest in the United States in mitigating wetland loss through banking and project-specific approaches. The carbon sequestration function is not currently considered as part of the wetland value. Hence, it is likely that carbon losses are occurring with questionable prospects for long-term parity. Accordingly, there is an opportunity to design mitigation systems to provide, and perhaps enhance, carbon sequestration functions. Wetlands are productive ecosystems. There is considerable opportunity to enhance that productivity while sustaining valued ecosystem functions at the landscape scale. However, development of integrated assessment systems based on knowledge of ecosystem processes is required.

5. Deserts and Degraded Lands (F. Blaine Metting and Rattan Lal)

Deserts and degraded lands are considered together because restoration of these ecosystems to sequester carbon can require highly manipulative strategies. Many of the same strategies can be applied to both systems, with some modifications.

The definition and areal extent of degraded lands is somewhat difficult to assess. Included under different definitions are both “natural” and anthropogenic degradation. Worldwide, there are approximately 1965×10^6 ha of degraded soils, 4% from physical degradation, 56% from water erosion, 28% from wind erosion and 12% from chemical degradation. With proper management these soils have the combined potential to sequester between 0.81 and 1.03 Gt C/year. Categories include saline, sodic, saline-sodic, mine spoils, and eroded or severely eroded soils.

Erosive processes are as a consequence of overly intensive tillage often combined with climate change and other inappropriate practices, such as use of marginal lands and steep topographies, and over grazing. One result is desertification. Estimates of land areas subject to degradation and desertification vary from $\sim 1\text{--}2.5 \times 10^9$ ha. Annual desertification rates vary from $\sim 5\text{--}27 \times 10^6$ ha, half of which is occurring on rangelands.

Depending on the basis for their definition (i.e., evapotranspiration or other aridity indices, vegetation, soil taxonomy), deserts account for between 11–12% of the Earth’s land surface. Estimates vary from 10^8 -to- $2^+ \times 10^9$ ha and include hyper-arid regions receiving <200 mm annual precipitation (ppt.) and arid areas with <200 mm of winter ppt. or <400 mm total annual ppt. Addition of semi-arid areas receiving 200–500 mm of winter ppt. or 400–600 mm of summer rainfall increases the areal extent of deserts to $\sim 5 \times 10^9$ ha. The principal feature of these regions is their negative water balance, which is reflected by generally sparse and often seasonal plant cover and low primary production. With open or absent plant canopies, much of the soil surface of deserts is exposed to full sunlight. One result is the evolution of unique microbial ecosystems dominated by autotrophic bacteria, microalgae and/or lichens known variously as cryptobiotic or algal crusts and desert pavement. Organic carbon stocks are much smaller than other ecosystems, but desert soils (primarily in the Aridosol soil order) often contain significant concentrations of inorganic carbon, principally as caliche. Other features of desert soils are:

- Aridosols occupy $\sim 1.7 \times 10^9$ ha
- Average carbon density of desert soils $\sim 3\text{--}3.5$ kg/m²/m depth
- World wide desert soil stock ~ 59 Gt total C, 4.7 Gt N
- Global caliche accretion rate ~ 0.05 Gt C/year

Strategies for enhanced carbon sequestration

Strategies for enhanced carbon sequestration have different objectives for deserts and degraded lands. For deserts, enhanced sequestration strategies are largely innovative uses of otherwise under utilized resources. Restoration of degraded lands and strategies to minimize or reverse desertification processes, on the other

hand, are as much aimed at reversing loss of carbon to the atmosphere as they are to enhancing sequestration. With the exceptions of the use of saline and brackish groundwater resources for (1) crop irrigation or (2) microalgal mass culture, strategies for deserts and degraded lands largely focus on below-ground sequestration. The greatest potential may be the discovery and application of innovative ways to enhance the accumulation of inorganic carbon stocks.

1. Control desertification (minimize, reverse) and restore degraded lands by means of improved land management practices
2. Delineate “bright” (trigger) spots for desert carbon sequestration. That is, identify area(s) to focus short-to-mid term desert carbon sequestration efforts.
3. Exploit under utilized desert resources to create wetlands and large-scale aquaculture projects with saline and brackish surface and groundwaters
4. Use existing plant and microbial resources together with biotechnology and genetic engineering:
 - Screen, identify and adapt C4 and CAM plants
 - Engineer enhanced water use efficiency, salt tolerance, high pH tolerance into select species for desert regions
 - Engineer for desired root physiology/metabolism and architecture
 - Encourage and manipulate surface and rhizosphere microbial communities to enhance sequestration
5. Expand the use of land application of organic and inorganic soil amendments:
 - Organic matter
 - Inorganic nutrients (e.g., Ca to enhance caliche development)
 - Microbial inocula to promote the development of desert crusts

Objectives

The objectives of the strategies for enhanced soil carbon sequestration in deserts and for restoration of degraded lands are to:

1. conserve soil and water, enhance water use efficiencies
2. utilize neglected and underutilized resources
3. strengthen/direct desired biogeochemical cycles/processes
4. enhance vegetal cover and effective carbon sequestration by plants and microbial communities

Research and development needs

Research and development needs for enhanced carbon sequestration in deserts and degraded lands falls within seven categories. These include research to establish global databases in biotechnology and land management, and to better understand natural plant, microbial, and soil processes and their interrelationships in arid and disturbed ecosystems. Specific research and development needs include:

1. *Quantify and categorize the extent and severity of degraded lands on a global scale.* The availability and quality of this information is inadequate. Campaigns to collect, archive and make available data are required to better

understand the extent of degraded lands and for developing effective and prioritized international research programs.

2. *Understand mechanisms and processes controlling carbon pools and fluxes in deserts and degraded lands.* A number of basic biogeochemical mechanisms important to establishing a solid, fundamental understanding of environmental and ecological processes in deserts and degraded lands are poorly understood. Research is needed to better understand the following:
 - Aeolian/dry deposition processes and effects on carbon sequestration
 - Inorganic carbon formation and movement and the role of Ca
 - Influence(s) of soil physical properties on carbon sequestration in arid regions, including the roles of texture, clay mineralogy, and soil structure and aggregation
 - Biogeochemical cycles/controls of carbon sequestration and movement, including N, P, S, Fe, Ca and Cl
 - The microbial ecology of desert soil surfaces and rhizosphere microbial communities
 - Physical, mechanical, and species-mediated weathering of exposed subsoil or parent material on eroded sites
3. *Management practices for desertification control and soil restoration*

Desert lands are, by definition, water limited. Thus, fewer than 10% of arid regions are cropped. Therefore, key management strategies for utilizing deserts and reversing desertification must focus on minimizing the water deficit. Important objectives are:

 - The use of appropriate plant species. In particular, many arid land plants have evolved special photosynthetic mechanisms for enhanced water use efficiency. These include the C4 photosynthetic fixation pathway and the crassulacean acid metabolism (CAM) pathway. There are many advantages to growing C4 and CAM plants in arid regions based on their improved water and soil nutrient use efficiencies at high temperatures. Research is needed to improve understanding of global biodiversity of C4 and CAM plants that could be screened for innate carbon sequestration traits of interest and used in field research projects.
 - Supplementary irrigation and the use of under utilized saline and brackish surface and ground waters. Growing crops or mass culturing microalgae that tolerate saline and alkaline water is another strategy for which expanded research efforts are required.
 - Research focused on techniques for soil erosion control, particularly as suited to arid lands is required. This research needs to be integrated with management efforts to optimize soil fertility, residue use, salinity control and the possible use of novel microbial and chemical amendments.
4. *Molecular biology and plant genetic engineering*

Biotechnology to improve plant performance in desert environments is needed and should focus on:

 - Development of genetic transformation tools and methods in new plant species for desert growth and carbon sequestration, including C4 and CAM plants.
 - Genetic engineering of desired traits into existing crop and forage plants, including salinity tolerance, water use efficiency, etc. One approach is to engineer desirable C4 and CAM metabolic traits into C3 crop plants.

5. *Microbial biology*

Microorganisms and microbial communities in and on desert soils are unique in comparison to agricultural and forest soils. In some arid and hyper-arid settings, microbial communities are the only mechanism for biological CO₂ fixation. They are also responsible for nitrogen input via biological N₂ fixation and for weathering of primary minerals and nutrient release. Fundamental research is needed in desert plant rhizosphere microbial community function and diversity of cryptobiotic communities (i.e., desert pavement, and lichen and microlagal crusts). In addition, applied research to develop and demonstrate microbial inoculants for rhizosphere and soil crust manipulation and development is needed.

6. *Desert ecology*

Ecosystem-scale research is required to better understand integrated ecological roles of desert plant and animal communities, including the role and global significance of arthropods in soil carbon cycling and sequestration. Ecological research is also needed to determine the appropriateness and extent of expansion or modification of grazing practices in arid and semi-arid regions.

7. *Economic, social and policy research*

In all cases, research is required for cost-benefit and risk analysis for all technical and management options for enhanced soil carbon sequestration in deserts and degraded lands. This includes the need for life cycle analysis all approaches to determine the overall energy and carbon budgets for implementation.

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6. Urban and Suburban Forested Areas (John Hom, David Nowak, Richard Pouyat, Marilyn Buford)

Carbon storage by urban forests nationally is estimated between 400–900 million tons (above-ground tree and shrub biomass only, Nowak 1995). Within the urban area, the largest carbon tree storage is found in institutional lands dominated by vegetation (e.g., parks, preserves, cemeteries, golf courses), in residential land use (1–3 family residential buildings), multiresidential areas (apartments) and vacant lots. Small trees account for the majority of the trees in urban areas. In comparison, U.S. forested ecosystems store approximately 52.5 billion tons of carbon (Birdsey 1992) and have 3–4 times higher live carbon/ha than urban forests, due to the lower average percent tree cover in urban sites (~28%). The estimates of suburban forest carbon storage are not well known, and are sometimes included in carbon estimates for urban forests, as they fall between the inventories of rural and urban forests.

Land use is one of the most significant factors affecting urban vegetation. Urbanization eliminated 10 million ha of agricultural and forested land in the United States between 1960 and 1980 (Alig and Healy 1987). It is estimated that 80% of the U.S. population will live in urban areas by the year 2025, up from 74% in 1986 (Alig and Healy 1987). Urban areas account for less than 1% of the total terrestrial life zones. The total amount of land dedicated to urban uses was 26 million hectares in 1992 (World Resource 1996).

Soil carbon densities for urban soils are relatively high compared to other biome types, higher than temperate forest soils, and comparable to wet boreal forest (17.5 and 23.7 kg/m², Pouyat, personal communication). Data suggest that long term urban forests soils may store more carbon than in rural forest soils with less labile carbon and greater passive carbon pools (Groffman et. al. 1995).

Urban forests are unique as they perform the dual function of directly sequestering atmospheric carbon and by indirectly conserving energy use of structures through shading, reducing the “heat island effect” by transpirational cooling, and reducing turbulent transfer losses. It was estimated that planting 10 million urban trees annually over the next 10 years would sequester and offset the production of 363 million tons of carbon over the next 50 years, with 20% due to direct carbon sequestration and 80% due to avoided carbon emission from energy conservation under optimal tree location. The total sequestration and energy offset of carbon reduction under this scenario is less than 1% of the carbon emissions projected for the United States over the same 50 year period (Nowak 1995).

Strategies

Urban forest planning and management to direct urban forest structure to desired outcome of increasing forest cover, increase rate of carbon capture, and long-term maintenance of standing stock within space and land-use limitations.

Sustain or enhance existing tree health to maximize sequestration while minimizing losses due to tree mortality (hold on to existing carbon).

Establish properly selected and located urban trees in available planting areas. Planning to maximize building energy conservation will yield greatest relative carbon benefit.

Objectives

Above-ground

1. Increase and maintain area of urban and suburban forested areas
2. Maximize biomass accumulation within space and land use limitations
3. Minimize mortality losses under multiple stress conditions within urban environment
4. Increase net carbon retention in maintenance (pruning), landfill (disposal), and recycling (leaf and chipping) practices.

R&D needs

Above-ground

Identify and select tree species and genotypes, for the urban and suburban environment that meets objectives of increasing sequestering carbon and reducing emissions.

Evaluate physiological responses and carbon allocation of urban trees and shrubs to those in rural environments. Urban trees are exposed to elevated CO₂ and temperature gradients within an urban-suburban environment as well as multiple stress interaction with ozone and atmospheric deposition of nitrogen and sulfur compounds.

Identify policy and management issues that would lead to preserving existing urban forests and increasing tree planting: energy conservation, economic development, natural resources planning, social-economic values.

Full life-cycle analysis on carbon budget of urban and suburban forests to increase carbon sequestration and reduce emissions. Trees in the urban environment require greater energy inputs in establishment, maintenance and disposal (fertilizer, site prep, pruning, leaf litter, chipping, transport and disposal). Trees offset energy use by energy conservation on buildings through shading, reduction of heat island effect, and turbulent transfer losses.

Objectives

Below-ground

1. Increase and maintain urban and suburban forest cover
2. Increase soil carbon densities
3. Employ planning and management practices to minimize soil, litter disturbance and maximize soil carbon retention

R&D needs

Below-ground

Will urban land uses result in greater soil carbon storage? Soil carbon densities for urban soils are relatively high compared to other biome types. Long term urban forests soils may store more carbon than in rural forest soils.

Determine litter quality changes and soil decomposition rates in the urban environment. The urban environment receives elevated chemical and atmospheric inputs. This can produce changes in litter quality by air pollution (ozone) or exotic plant species. Temperature increases in the urban environment and greater nitrogen deposition will increase decomposition rates. Heavy metal and air pollution damage to plant tissue should decrease decomposition rates. Changes in microbial and soil invertebrate composition across urban to rural environments may change rates of decomposition.

Develop urban land use management practices to increase soil carbon. Management practices, such as irrigation and fertilization make up for site limitations restricting plant and root growth.

Investigate effects of drastic soil disturbances that occur in urban areas on soil carbon

Links to other ecosystems:

1. Determine the net conversion of land use (i.e., agricultural and forested lands to suburban and urban forested lands).
2. Determine extent of urban land uses in other vegetation life zones (e.g., coastal areas, wetlands conversion to urban and suburban use).

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Table B.1 Assessment of carbon storage and sequestration by urban forests in the United States

Regi- on	Urban land ¹	Urban tree cov ²	Total C stored ³	Total C gr. seq ⁴	Total C net seq ⁵	Per meter stored ⁶	Per meter gr. seq ⁷	Per meter net seq ⁸
NE	48,646	15,814	131,876,000	4,668,000	679,000	2,718	95.9	13.8
NC	51,724	17,118	142,748,000	5,052,000	735,000	2,768	97.6	14.3
SE	46,413	15,562	129,775,000	4,593,000	668,000	2,792	98.8	14.3
SC	65,930	15,926	132,807,000	4,701,000	684,000	2,026	71.4	10.4
RN	5,331	2,402	20,028,000	709,000	103,000	3,756	132.9	19.3
RS	22,447	2,447	20,407,000	722,000	105,000	914	32.1	4.7
PSW	27,348	2,949	24,589,000	870,000	127,000	890	31.9	4.7
PNW	7,958	2,537	21,155,000	749,000	109,000	2,669	94.1	13.6
GP	4,710	907	7,562,000	268,000	39,000	1,606	56.8	8.2
Misc ⁹	492	142	1,183,000	42,000	6,000	2,397	85	12.4
U.S. ¹⁰	281,000	75,803	632,129,000	22,373,000	3,255,000	na	na	na

Ref. David J. Nowak, Daniel E. Crane, and Jack C. Stevens, personal communications-DRAFT

Note: all urban tree carbon numbers are for aboveground only

¹ urban land in km²

² urban tree cover in km²

³ total carbon stored in metric tons (t)

⁴ total gross annual carbon sequestration in metric tons (t/year)

⁵ total net annual carbon sequestration in metric tons (t/year)

⁶ carbon stored per acre of land (g/m²)

⁷ gross annual carbon sequestration per acre of land (g/m²/yr)

⁸ net annual carbon sequestration per acre of land (g/m²/yr)

⁹ Miscellaneous land-urban land that crossed state borders and could not be assigned to an individual states

¹⁰ U.S. total

na-not analyzed

U.S. Regions:

Northeast (NE): NY, PA, MD, WV, DE, NJ, CT, RI, MA, NH, VT, ME, DC

North Central (NC): MN, IA, MO, IL, WI, MI, IN, OH

Southeast (SE): VA, NC, SC, GA, FL

South Central (SC): KY, TN, AL, MS, AR, LA, OK, TX

Rockies-north (RN): MT and ID.

Rockies-south (RS): NV, UT, AZ, CO, WY, NM

Pacific SW (PSW): CA

Pacific NW (PNW): OR, WA

Great Plains (GP): ND, SD, NE, and KS

Table B.2. Urban soil carbon storage

Life zone groups	Area* (x 10 ¹² m ²)	Carbon density(kg m ²)	Soil carbon (x 10 ¹⁵ g)
Tropical forest-moist	5.3	11.4	60.4
Temperate forest-warm	8.6	7.1	61.1
Boreal forest-wet	6.9	19.3	133.2
Warm desert (1)	14.0	1.4	19.6
Wetlands (2)	2.8	72.3	202.4
Urban (3)	0.26	20.6	5.4
Urban -15% (4)	-	17.5	4.6
Urban +15%	-	23.7	6.2

* After Olson

1. Ratio of warm desert to cool desert after Walter
2. Carbon density for cultivated land and wetland after Schlesinger
3. After Hyun-Kil Jo and E. G. McPherson
4. Assuming error of + and - 15% to give range of urban soil carbon data

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